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STRUCTURAL AND ECONOMIC OPTIMIZATION OF OFFSHORE WIND TURBINE SUPPORT STRUCTURE AND FOUNDATION

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ABSTRACT: A joint consensus agrees that the use of offshore wind turbines can assist to the energy supply. One of the major drawbacks in using offshore wind turbine farms has up to recent days been the extremely high foundation cost. In 1996 the development of a tripod based foundation for offshore wind turbines was initiated. The structure is very similar to a traditionally piled tripod, used for minor oil/gas platforms. Recently a cost-efficient structure combined with a bucket foundation has been developed for large offshore wind turbine farms.

This new structure-bucket foundation has been compared to the traditionally tripod with driven steel piles at a water depth of 11 m, at two potential locations for new offshore wind turbines in Denmark. Rødsand primarily consisting of clay till, and Horns Rev, a dense sand location.

The special loading schemes in connection with offshore wind turbines, the development of the new structure and the bucket foundation versus driven steel pile comparison are described in this paper. The optimised structure resulted in a diminished amount of steel and minor total costs.

The development of the new optimised structure and the comparison between the bucket foundation and the steel piled tripod was part of a larger R&D project. The consulting engineers Nellemann, Nielsen & Rauchenberger A/S (NIRAS), Danish Geotechnical Institute (DGI), RISØ and RAMBØLL undertook in co-operation the R&D project with the Danish power station engineering company SEAS. The project was partly financed by the participants and by the Danish Energy Agency through their 1998 Energy Research Program UVE-98.

RAMBØLL was responsible for the development and comparison of the bucket vs. steel pile tripod structure. NIRAS worked with a gravity-based solution, RISØ delivered dynamic wind loads measured on their wind turbines while DGI examined the hydraulic instability in the soil during installation.

1 OFFSHORE WIND TURBINES

The use and development of wind turbines has been a hot topic in the debate of energy political and environmental issues for the last couple of years.

Denmark has for many years been on the absolute leading edge of wind turbine technology both with respect to research, manufacturing and operation. Out of the 5 leading manufactures of wind turbines 4 are based in Denmark.

A joint consensus agrees that the use of offshore wind turbines can assist to the energy supply. One of the major drawbacks in using offshore wind turbine farms has up to recent days been the extremely high foundation cost (¼ of total cost).

1.1 Historical Background

In 1991 the Danish power station Elkraft constructed the world's first offshore wind turbine farm at Vindeby consisting of 11 turbines with a total rated capacity of 5 MW. Following this the power company Midtkraft erected 10 turbines at Tunø Knob in 1995 also with a rated capacity of 5 MW.

One of the lessons learned from these earliest offshore farms has been that installation of the offshore parks is approximately 50-100% more costly per installed rotor area as compared to conventional onshore projects. The reasons for this are primarily the added complexity of having to install foundations and power cables offshore and secondly the increased costs of the foundation itself.

The Danish government initiated in June 1996 a plan of action for energy dealing with a sustainable energy development toward the 21st century, followed by a political agreement in November 1996 that offshore-based wind turbines is an area to be given special attention on the governmental finances.

2 THE FIRST R&D PROJECT

As a result of the political consensus an R&D project was initiated in 1996 (RAMBØLL et al., 1997) aiming at developing new foundation concepts in order to reduce the foundation costs and thus the overall costs of the offshore wind turbines.

The study was based on leading manufacturer's estimate of a 1.5 MW pitch regulated wind turbine specifically designed for offshore operation. This turbine was believed to be the preferred turbine for large offshore wind turbine parks in the year 2000. Today it is more likely a 2.0 or even a 2.5 MW pitch that will be the preferred turbine for large wind turbine parks.

2.1 Locations, Loading and Soil Conditions

Five locations in Danish waters were identified in 1995 as potential locations for future offshore wind turbine parks. The locations are Horns Rev, south of Læsø, Omø Stålgrunde, Gedser Rev and Rødsand. Two of these locations were chosen for the actual R&D project, being Horns Rev west of Esbjerg on the Jutland peninsula and Rødsand west of Gedser at the southern tip of the island Lolland in east Denmark. The locations are indicated on Figure 2.1. The two locations have been chosen as they represent two extremes in terms of soil conditions, with Horns Rev being a dense sand profile and Rødsand constituting very hard clay till formations.

In terms of environmental actions Rødsand is typical for the conditions found in inner most Danish waters with relatively shallow water, breaking extreme waves and possibly drifting solid sea ice during the winter season.

Horns Rev on the other hand represents the harsh North Sea environment as found along the west coast of Jutland, with fairly large (breaking) waves and large swells even in the calm summer months.

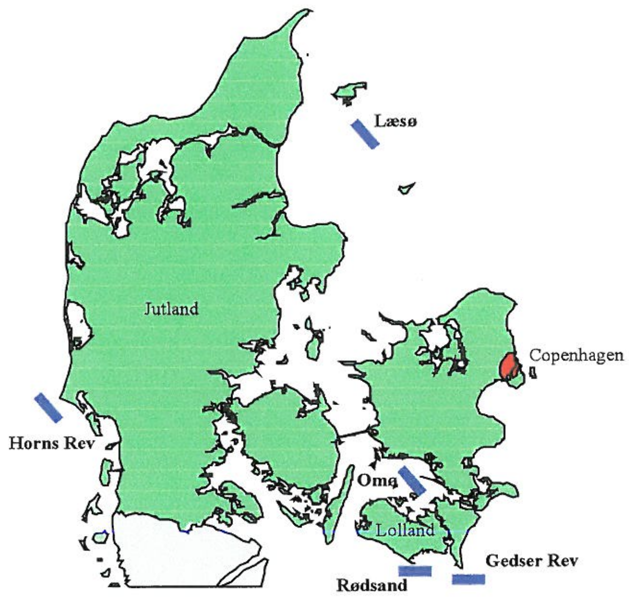

Figure 2.1 Chosen locations for future offshore wind turbine parks in Denmark. Two sites are used in this study, Horns Rev west of the Jutland peninsula and Rødsand at the southern tip of Lolland.

During the fall of 1998 RAMBØLL carried out the geotechnical and geophysical preinvestigations for Horns Rev and the water south of Læsø using various subcontractors. The Geotechnical and geophysical investigations for Omø Stålgrunde and Rødsand are planned for the spring of 1999. The investigations for the Gedser Rev are still pending.

2.2 Comparison Between Three Different Foundation Types

The '96 R&D project consisted of three foundation concepts; gravity based foundation, mono pile foundation and tripod foundation.

The gravity foundation was a further development of the trusted concept applied at the two earlier parks, and from the beginning thought of as a concrete structure to provide the weight required. The concept shown in Figure 2.1a was undertaken by NIRAS.

The mono pile foundation was based on a very large diameter monopile originally known from the offshore industry. Within the past years they have also been applied as foundation for offshore wind turbines. LICengineering A/S carried out the study of this concept illustrated in Figure 2.1b.

The tripod foundation was based on a concept applied for a number of years for platforms for marginal fields within the oil/gas industry and is as such a well-proven concept. RAMBØLL performed the development of the braced steel tripod fixed to the seabed by use of open-ended steel piles. The structure connected three steel piles located at a distance from a central element attached to the turbine tower. See Figure 2.1c. The three concepts and the loading schemes (ice, wind, waves) are described in detail by Juhl et al. (1997).

The R&D project revealed a number of conclusions and observations:

- All three concepts are preferred to be steel concepts. The primary draw backs of the concrete structures are the overall weight which complicates transport and installation operations, and the requirements to build the structures at a temporarily established construction yard close to the final location of the park which imposes restrictions on weather.
- The study (for water depths of 5 to 11 m) resulted in reduced estimated foundation costs (16% of total costs) compared to the experienced 23% of total costs at the existing wind turbine farms.

- A rather weak dependency of depth, for all three concepts, disqualified the expected "quadratic rule", which forecasts the costs of the completed foundation to be approximately proportional with the water depth squared.
- The bigger the turbine – the smaller the relative foundation costs.
- While most of the differences in costs between the three concepts analysed – in spite of all effort – really lies within the tolerance/uncertainty, the tripod concept seems to have the lowest costs at greater water depth. Likewise the gravity structure is the cheaper concept on shallow water with ice.
- Some advantages and disadvantages of the three concepts are given in the Table 2.1.

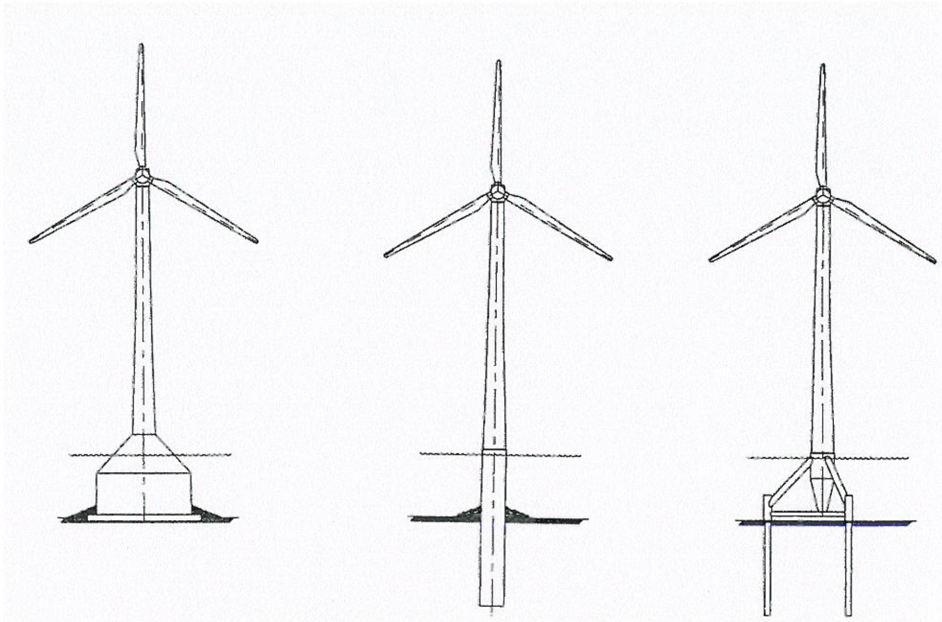

Figure 2.2 The three concepts as envisioned at project start
a) Concrete gravity foundation, b) Steel mono pile and c) Steel tripod.

Table 2.1 Advantages and disadvantages for the three foundations types.

Foundation type	Advantages	Disadvantages
Gravity steel structure	No piling Can be removed completely and possibly repositioned All parts visible for inspection	Seabed preparations required Time consuming welding details Space requirements at construction site
Mono pile steel structure	Simple No preparations of seabed Insensitive to scour	Requires heavy duty piling equipment Not suited for geotechnical location with large boulders
Tripod steel structure	Adaptable to increased water depth Low blocking effects A minimum of preparations required at site prior to installation	Specialised fabrication methods Not suitable for geotechnical location with large boulders Not suitable for shallow water depths (< 6 m)

2.3 Tripod Steel Pile Solution

The concept is based on the experience with lightweight and cost-efficient three-legged steel jackets for the marginal fields in the oil/gas industry. The concept consists of a steel space frame transferring the sectional forces from the tower to primarily bending moments, tension and compression loads in three hollow steel piles driven into the seabed.

Each leg frame consists of a pile, a pile sleeve and two braces. The legs are interconnected above the seabed by three mudbraces giving the tripod its characteristic triangular base. A typical layout for a tripod foundation at 8-11 water depth is depicted in Figure 2.3 and in Figure 2.4. The tripod is placed on the seabed.

It was found that the optimal pile is a 36" (OD 914 mm) hollow steel pile with a wall thickness varying from 16 to 43 mm depending on location and the position of the pile being inclined 8°. The pile is driven 20-21 meters into the seabed at the dense sand, Horns Rev, whereas the very stiff soil at Rødsand despite ice loads only requires a penetration of 10-11 meters.

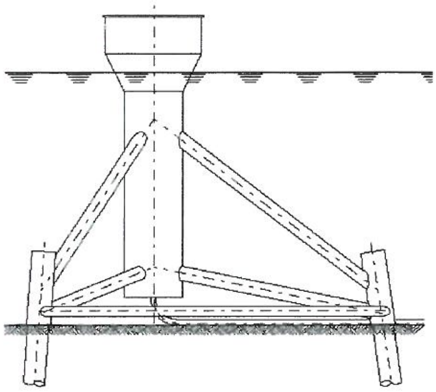

Figure 2.3 Side view of optimised tripod layout.

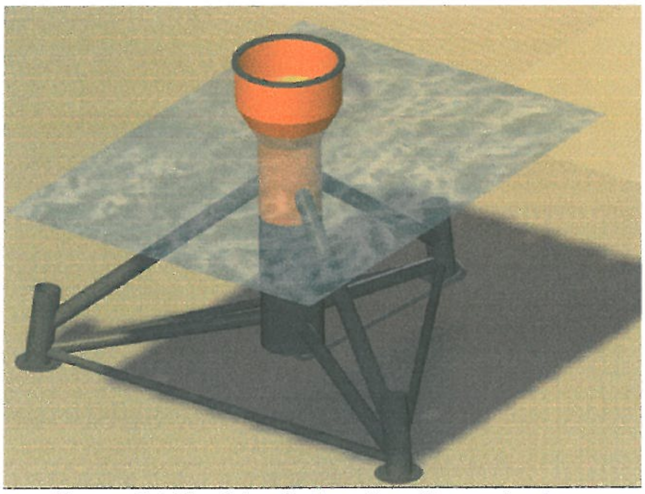

Figure 2.4 The tripod placed on the seabed

The tripod concept is described in detail by Juhl et al.(1997) and RAMBØLL (1997).

3 NEW SOLUTION TRIPOD-BUCKET FOUNDATION

3.1 Loading Schemes

The wind loads on a slim structure such as the offshore wind turbines give rise to a constant average load, combined with a variable load changing between positive and negative peak values around every 2 seconds. This loading scheme can be approximated by a sin-curve.

Traditionally the foundation of the wind turbines is designed to withstand the maximum load at all time.

Thus the foundation will generally be designed for too large a load, therefore a structure designed to withstand the actual load scheme would be optimal.

A possible solution to the above-mentioned problem is using a foundation based on suction buckets. At a load compression situation the foundation would work as a normal foundation. In case of load tension, the buckets would work by a combination of skin friction on the inside and outside of the buckets, and the suction due to negative pore pressure under the lid could withstand the brief peak values. Thus the design load could be diminished, as the suction would carry part of the peak values.

No plastic displacements are expected due to the mean load, thus the tower can maintain verticality. However the effect of cyclic degradation has been examined in Phase 1.

3.2 Development of New Optimised Structure

The idea of the new optimised structure is that three buckets replace the three piles. By the use of buckets rather than piles it is possible to remove some of the geometric constraints that formed the structure before. It is now possible to extend the centre column (the tower) to seabed and then use the base of the column as one of the buckets. In that way the structure now consists of a centre column and 2 supported frames which are placed perpendicular to each other. The centre column (the tower) and the buckets on the supported frames will be penetrated to the same depth below mudline by means of suction. The centre column and the supported frames are steel tubes. Due to the reduction of the maximum capacity of compression when having a bending moment the structure is optimised in a way that the bending moment is reduced.

The removal of some of the frames reduces the amount of steel. The advantage of the new structure is, besides the smaller amount of steel, that it now is possible to berth from the side without steel frames - 270°. Scour protection around the buckets is necessary in frictional materials.

Figure 3.1 The new optimised structure.

4 BUCKET

4.1 The Development of the Bucket Dimensions

The estimation of structure and buckets was done simultaneously. The structure was modelled in ROSAP, RAMBØLL´s Offshore Structure Programme. In this programme the buckets were modelled as short stiff piles. To recreate the side friction, skin friction and tip resistance the piles were supplied with springs representing the soil curves. Two springs were placed on the tip to ensure stiffness against bending moment and the sliding resistance (rocking spring stiffness and sliding spring stiffness). The stiffness of the bucket against translation and rotation was modelled in the model by:

- P-Y curves, representing the lateral resistance on the sides of the bucket corresponding to earth pressure.
- A horizontal spring of rotation that acted between the surroundings and the bottom of the bucket in the horizontal plane. The spring simulated the friction and resistance from the bottom of the soil plug, against movement from the surrounding soil.
- A spring of rotation that acted against all rotations in the horizontal plane. The spring was modelled according to API procedure.

To enable the penetration of the bucket it was a condition that the required suction to penetrate the soil was less than or equal to the critical suction. The required suction was determined and a study of the critical suction was done. In both cases the required suction was minor than the critical suction. By applying suction less than critical suction no cavitation during installation will occur.

Critical suction can be defined as the maximum possible partial vacuum applied on a bucket without soil plug lifting or dilating. For sand the critical suction is based on a stationary steady state flow with a H/D relationship less than 0,5 (Clausen and Tjelta, 1996). For clay the critical suction can be defined in terms of an inverse rupture surface.

The estimation resulted in the below given dimensions:

Table 4.1 Estimated bucket dimensions for the two locations.

	Height [m]	Diameter [m]	Thickness [mm]
Horns Rev (sand)	2,1	4,2	30
Rødsand (clay till)	1,3	2,6	30

4.2 Pull-Out Capacity

The pullout force was investigated in both cases. The pullout force was calculated using the general bearing capacity formula for clay. The formula for clay was used on sand, as well. The internal frictions in the sand was equalised with an undrained shear strength from the assumption that sand will act as an undrained material with undrained shear strength for quick, short duration peak loads (Hansen, 1976).

The pullout force was for the two locations determined as:

$T_{Rødsand}$ = 3,6 MN
$T_{Horns\ Rev}$ = 4,0 MN

4.3 FEM Analysis of Bucket

To verify the calculations of the pullout force for the bucket at Horns Rev (sand location) a 2 dimensional FE-model of bucket and surrounding soil was made in the FE-programme ABAQUS.

The bucket and soil was modelled using axisymmetrical elements, therefore only a cross-section from the middle of the bucket to the wall and the surrounding soils was modelled. The sand was modelled using the Drucker-Prager material Model. The steel bucket was modelled as a purely elastic material.

In the FE-analysis an increasing tension load was applied to the bucket until the maximum pore pressure in the bucket was achieved corresponding to theoretical full vacuum. Figure 4.1 shows a deformation figure of the bucket and soil in the tension situation.

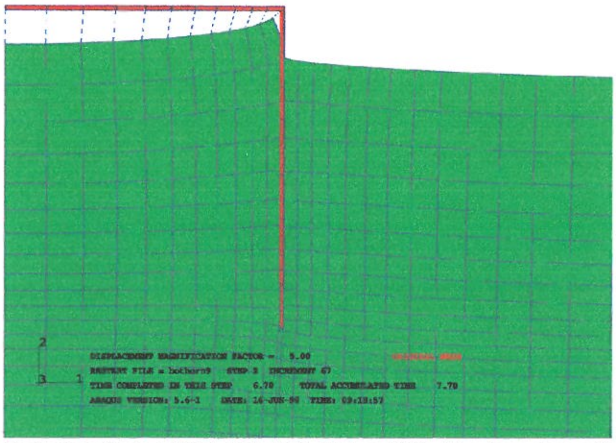

Figure 4.1 Deformation of the bucket and soil in the tension situation. The figure is drawn with a magnification factor 5.

The force at that time was compared to the estimated value. The FE-value was determined to 6.7 MN. This value was bigger than the value determined earlier which lead to the conclusion that the calculated values based on simple assumptions were conservative.

In Figure 4.2 the pore pressure distribution is depicted at the failure situation. The figure depicts solely the soil.

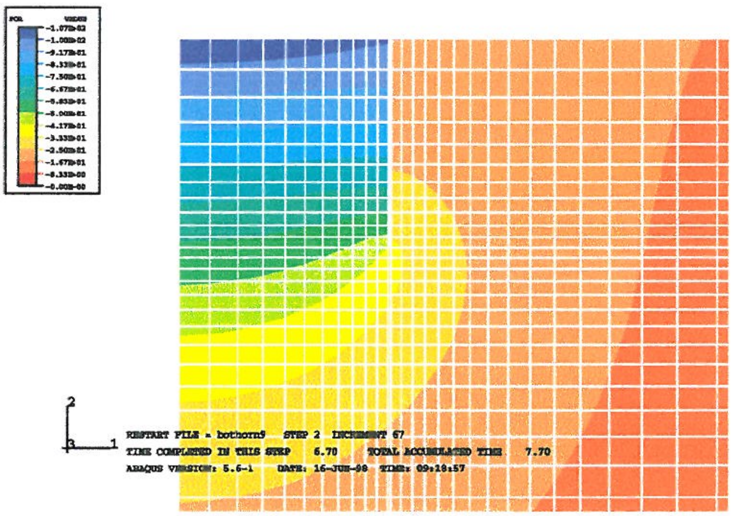

Figure 4.2 Pore pressure distribution at the failure situation. Dark blue colour corresponds to –100 kPa (theoretical full vacuum).

5 NEW STRUCTURE VERSUS OLD

The new optimised structure founded on buckets has been compared to the steel pile tripod, especially with respect to structural and economical impact.

As the structure has been changed relative to the steel pile tripod the amount of steel was significantly reduced. The difference in amount of steel between the two concepts is shown in Table 5.1.

Table 5.1 The amount of steel for the different locations and concepts.

	Horns Rev		Rødsand	
	The steel pile tripod	The steel bucket tripod	The steel pile tripod	The steel bucket tripod
Weight of structure [kg]	75797	68353	84824	65227
Weight of foundation [kg]	26844	28531	32562	12730
Total weight [kg]	102641	96884	117386	77957

For all cases except the buckets at Horns Rev there was a reduction in the amount of steel as shown in Table 5.1. The fact, that the dense sand conditions at Horns Rev required fairly large bucket dimensions, resulted in approximately the same amount of steel as the piled solution. Further the dimensions of the buckets are based on the calculations according to the general bearing capacity formula, which is believed to be on the conservative side. Some of the cutback at Rødsand can be explained by a reduction of the ice load compared to the first R&D project (Juhl et al., 1997)

The price of steel will change when going from piles to buckets, as the buckets require more welding during fabrication.

The figures Figure 5.1 through 5.4 depict the distribution of the individual parts in percent of the total price. The price for the geotechnical investigations and detailed design together with the installation is unchanged between the steel pile tripod and the steel bucket tripod, even though a bucket foundation requires shorter geotechnical borings.

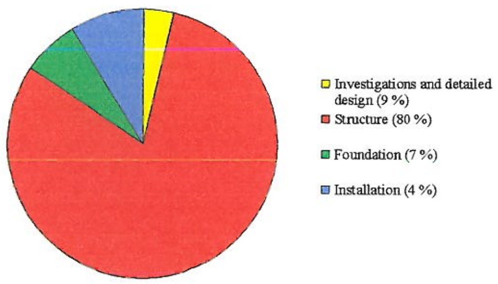

Figure 5.1 The steel pile tripod – Horns Rev.

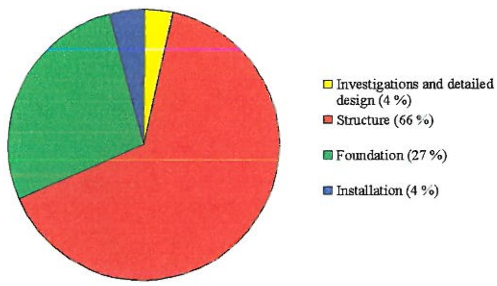

Figure 5.2 The steel bucket tripod – Horns Rev.

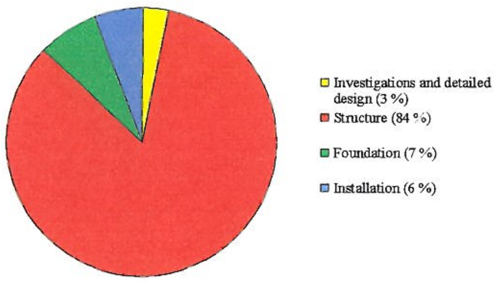

Figure 5.3 The steel pile tripod – Rødsand.

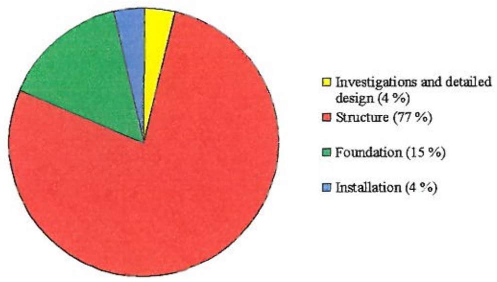

Figure 5.4 The steel bucket tripod – Rødsand.

6 CONCLUSIONS

A new structure-bucket foundation has been developed and compared to a traditional tripod with driven steel piles, at water depth of 11m, at two potential locations for new offshore wind turbines.

The comparison between the two concepts revealed the following results:

- A general saving on the amount of steel for the structure, corresponding to 10% at Horns Rev and 23 % at Rødsand.
- A 61% saving on the amount of steel for the foundation at Rødsand, and a 6% increase at Horns Rev.
- A general steel weight saving between 6 and 34 %.

Due to the difference in steel prices (including welding during fabrication), the two foundation concepts revealed approximately the same price at Horns Rev and a large saving at Rødsand. However with a reduced amount of steel for the bucket foundation at both locations.

Installationwise the suction bucket tripod is appealing, as the installation time is substantially reduced and less resource demanding.

Generally the new bucket tripod foundation is economically and environmentally attractive in clay and soft soils. In dense sand as found at Horns Rev, the advantages are less, when dealing with lighter offshore structures such as wind turbines. However other investigations indicate saving of 5% for dense sand and 15% at cohesive soils, when platforms are founded on buckets instead of driven pile (Rognlien et al., 1991).

Based on the results found in 1998, the R&D project will continue in an ongoing phase, where the load spectrum will be analysed in detail, and a more complex FE model (3D model) will be established. The next phase is briefly described at the end of this paper.

7 ACKNOWLEDGEMENTS

The development of the new optimised structure and the comparison between the bucket foundation and the steel piled tripod was part of a larger R&D project (RAMBØLL, 1998). The consulting engineers Nellemann, Nielsen & Rauchenberger A/S (NIRAS), Danish Geotechnical Institute (DGI), RISØ and RAMBØLL in co-operation undertook the R&D project with the Danish utility engineering company SEAS. The project was partly financed by the Danish participants and by the Danish Energy Agency through their 1998 Energy Research Program.

RAMBØLL was responsible for the development and comparison of the bucket vs. steel pile tripod structure. NIRAS worked with a gravity-based solution, while DGI examined the hydraulic instability during installation.

7.1 Next Phase

During the next phase the idea is to establish a detailed estimation of the behaviour of the bucket.

This is planned being done using a 3-dimensional FE-model applying a more complex soil model than the Drucker-Prager Model, the Modified Friction Model (Kavli et al., 1996) and/or the Mohr-Coulomb Model. For the determination of the parameters for the model a number of laboratory tests (triaxial, odometer) will be performed. In addition the tests will be performed not only on dense sand and clay till but also on clay from the latest Ice Age (Yoldia). As this clay has been found on one of the future locations for offshore wind turbine farms, the water south of Læsø. RAMBØLL and NIRAS are to perform the modelling, while all laboratory tests will be carried out at DGI.

Instead of a stationary wind load used in the preliminary work, the dynamic wind loads from RISØ corresponding to measured loads on wind turbines will be used. By using the true loads it will be possible to investigate how the capacity depends on the loading velocity. Besides the investigations of the dynamic behaviour of the buckets the influence of an eccentric load on a bucket will be investigated.

The model tests performed by DGI on hydraulic instability will be compared to some additional tests made on a larger bucket, in order to investigate the scale effect.

The structure and foundation will further be optimised and a lifetime analysis (LCA) will be performed and the aspects of less amount of steel compared with the increased price of steel will be accounted for. Furthermore the easy removal of the structure and foundation will be included.

At this time it is the intention to extend the R&D project to include a number of large scale tests (full scale) performed on both a sand location and location consisting of clay.

8 REFERENCES

Clausen, C. J. F., Tjelta, T. I, 1996, "Offshore Platforms Supported by Bucket Foundation", *XV IABSE Conference*, pp. 819-829.

Hansen, B, 1976, "Modes of Failure under Inclined Eccentric Loads", *BOSS* '76, pp. 488-500.

Kavli, A., Nordal, S., Askevold, A., 1996, "*Description of the swelling version of the Mobilized Friction Model (SWMFM)*", SINTEF Civil and Environmental Engineering, Trondheim, Norway.

Juhl, H., Lorin Rasmussen, J. Birck, C., Lyngesen, S., 1997, "Cost-efficient Foundation Structures for Large Offshore Wind Farms", *OWEMES '97 Conference*, pp. 397-410.

RAMBØLL, NNR, LIC ENGINEERING A/S, ELSAMPROJEKT A/S, SEAS, 1997, "*Vindmøllefundamenter i havets- slutrapport*", ELSAMPROJEKT A/S, Fredericia, Denmark, (in Danish).

RAMBØLL, 1997, "*Vindmøllefundamenter i havet, EFP-96, J.nr. 1363*/96-0006, Tripod Foundation, Volume 1 – Report*", RAMBØLL, Virum, Denmark, (in Danish).

RAMBØLL, 1998, "*Havmøllefundamenter med sug, Fase 1-rapport*". RAMBØLL, Virum, Denmark, 1997, (in Danish).

Rognlien, B., Eriksen, K., Sparrevik, P., Baerheim, M. 1991, "Caisson Foundation for Jacket Structures. "*International Offshore and Polar Engineering Conference*", pp. 207-214.

AGEP: Foundation Engineering papers

1 Sørensen, C.S., Steenfelt, J.S., Mortensen, J.K. (1995). Foundation for the East Bridge for the Storebælt Link. *Proc. 11th Eur. Conf. Soil Mech. & Fndn. Engng. Copenhagen*. Danish Geotechnical Society, Bulletin 11, Vol 5, pp 5.31-5.42. Also in *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9506.

2 Steenfelt, J.S., Hansen, H.K. (1995). Key Note Address: The Storebælt Link - a geotechnical view. *Proc. 11th Eur. Conf. Soil Mech. & Fndn. Engng. Copenhagen*. Danish Geotechnical Society, Bulletin 11, Vol 10, pp 10.11-10.40. Also in *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9509.

3 Feld, T., Sørensen, C.S. (1996). Structure-Foundation Interaction on the Storebælt Link East Bridge. *Proc. Int. Conf. for Bridge and Struct. Eng., Copenhagen,* pp 809-818. Also in *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9601.

4 Sørensen, C.S., Jensen B.S. (1996). Fod-pælens bæreevnetilvækst. *Proc. Nordic Geotechnical Meeting, NGM-96, Reykjavik*, Vol 1, pp 253-258. Also in *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9606.

5 Sørensen, C.S., Faber, M.H., Stenstrup, B. (1997). Reliability Based Reassessment of an Existing Pile Foundation. *Proc. XIV Int. Conf. on Soil Mechanics and Foundation Eng., Hamburg*, Sept. 6-12 - 1997, pp 1197-1200. Also in *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9709.

6 Steenfelt, J.S. (1997). Type A prediction of settlements for railway box culvert in road embankment on clay till. *Proc. XIVth International Conference on Soil Mechanics and Foundation Engineering, Hamburg,* Vol 2, pp 1037-1044. Also in *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9710.

7 Sørensen, C.S., Steenfelt, J.S., Mortensen, J.K., Hansen, Aa., Gluver, H. (1998). Foundation of the East Bridge. In *"East Bridge"*, published by A/S Storebæltsforbindelsen, pp 97-110, ISBN 87-89366-91-3. Also in *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9813.

8 Sørensen, C.S., Hededal, O. (1999). Geotecnical design considerations for Storebælt East Bridge and Øresund Bridge. *Proc. IABSE Colloquium, Foundation for Major Bridges-Design and Construction*, New Delhi, India, pp. 25-30 . *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9817.

9 Hededal, O., Sørensen, C.S. (1999). Elasto-plastic foundation analysis of ship collision to The Øresund High Bridge. *Proc. IABSE Colloquium, Foundation for Major Bridges-Design and Construction*, New Delhi, India, pp. 175-180. *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9818.

10 Sørensen, C.S., Bisgaard, A., Hededal, O. (1999). Foundation of the Øresund Bridge. *Proc. XIIth Eur. Conf. Soil Mech. Geotechn. Eng.,* 7- 10 June 1999, Vol. 1, pp. 609-616. *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9819.

11 Steenfelt, J.S., Jørgensen, M.B., Jørgensen, P.O. (1999). Preloaded motorway embankments - an environmentally sound solution for soft soil areas. *Proc. XIIth Eur. Conf. Soil Mech. Geotechn. Eng.* , 7- 10 June 1999, Vol. 3, pp. 1583-1592. *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9820.

AGEP: Foundation Engineering papers

12 Feld, T., Petersen, S.J. (1999). Establishment of Foundation Design Parameters for Limestone. *Proc. IABSE Colloquium, Foundation for Major Bridges - Design and Construction,* New Delhi, India, 24-26 Feb. 99, pp. 51-56. *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9901.

13 Feld, T. (1999). Development of the load-deformation curve for bridge piers subjected to ship impact. Published in *Proc. XIIth Eur. Conf. Soil Mech. Geotechn. Eng.,* 7- 10 June 1999, Vol. 1, pp. 737-742. *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9902.

14 Rasmussen, J.L., Feld, T. (1999). Pile Driving Fatigue Damage. A Case Story. Published in *Proc. XIIth Eur. Conf. Soil Mech. Geotechn. Eng.,* 7- 10 June 1999, Vol. 2, pp. 577-582. *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9903.

15 Feld, T., Rasmussen, J.L., Sørensen, P.H. (1999). Structural and Economic Optimization of Offshore Wind Turbine Support Structure and Foundation. Published in *Proc. OMAE-99, 18th Int. Conf. on Offshore Mechanics and Arctic Engineering,* St.Johns Nfld. Canada July 99. Vol ?, pp. ? *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R9904.

16 Sørensen, C.S., Jensen, B.S. (2000). Skråningsstabilitet. Accepted for publication in *Proc. Nordic Geotechnical Meeting, NGM-2000,* Helsinki, June 5.-7.2000. *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R2004.

17 Jensen, B.S., Sørensen, C.S. (2000). Effektivisering af forbelastning ved anvendelse af vertikaldræn. Accepted for publication in *Proc. Nordic Geotechnical Meeting, NGM-2000,* Helsinki, June 5.-7.2000. *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R2005.

18 Feld, T., Leth, C.T., Mikkelsen, H., Steenfelt, J.S. (2000). Nyt laboratorieudstyr til simulering af dynamisk påvirkede sugebøttefundamenter. Accepted for publication in *Proc. Nordic Geotechnical Meeting, NGM-2000,* Helsinki, June 5.-7.2000. *AAU Geotechnical Engineering Papers*, ISSN 1398-6465 R2006.